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# Joint light tactical vehicle and mine resistant ambush protected all-terrain vehicle optimum procurement ratio

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# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**JOINT LIGHT TACTICAL VEHICLE AND MINE RESISTANT AMBUSH PROTECTED ALL-TERRAIN VEHICLE OPTIMUM PROCUREMENT RATIO**

by

Kyle E. Mattox

December 2012

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This thesis builds an optimization decision model that can be used to determine the optimum ratio of the two vehicles that the Army and Marine Corps can purchase to minimize costs while taking into account constraints related to each vehicles' capabilities, such as required off-road capabilities and transport ease for missions supported by the services. The proposed optimization decision model is a cost minimizing non-linear programming model that also accounts for changes in the average production cost of each type of vehicle by embedding a cumulative average cost formula into the objective function of the model.

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Submitted in partial fulfillment of the
requirements for the degree of

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This thesis builds an optimization decision model that can be used to determine the optimum ratio of the two vehicles that the Army and Marine Corps can purchase to minimize costs while taking into account constraints related to each vehicles' capabilities, such as required off-road capabilities and transport ease for missions supported by the services. The proposed optimization decision model is a cost minimizing non-linear programming model that also accounts for changes in the average production cost of each type of vehicle by embedding a cumulative average cost formula into the objective function of the model.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| CSV | Combat Support Vehicle |
| CTV | Combat Tactical Vehicle |
| DoD | Department of Defense |
| EMD | Engineering, Manufacturing & Development Phase of Acquisition Process |
| FoV | Family of Vehicles |
| GAO | U.S. Government Accountability Office |
| HMMWV | High Mobility Multipurpose Wheeled Vehicle |
| IED | Improvised Explosive Device |
| JLTV | Joint Light Tactical Vehicle |
| LTV | Light Tactical Vehicle |
| LTWV | Light Tactical Wheeled Vehicles |
| M-ATV | Mine Resistant Ambush Protected All-Terrain Vehicle |
| MRAP | Mine Resistant Ambush Protected |
| TD | Technology Development Phase of Acquisition Process |
| TWV | Tactical Wheeled Vehicle |

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# I. INTRODUCTION

The Armed Forces of the United States face many new threats while in combat operations. Among these threats are those posed by improvised explosive devices (IED). The Army and Marine Corps initially responded to the IED threat in 2003 by adding armor to the High Mobility Multipurpose Wheeled Vehicle (HMMWV); however the weight of the added armor on the HMMWV deteriorated the vehicle's automotive performance to the point that adding addition armor was no longer prudent. In 2007, the Army and Marine Corps began building Mine Resistant Ambush Protected (MRAP) vehicles.

In 2009, as the magnitude of the war in Iraq began to decline and efforts shifted to the war in Afghanistan, the limits of the MRAP were exceeded, as the size and weight of the vehicle are too great to be effective in the high altitude rugged terrain. A lighter version of the vehicle was needed to navigate the high mountain roads of Afghanistan while still providing protection from IEDs. The urgent need was filled by the MRAP All-terrain Vehicle (M-ATV). This vehicle is much more capable off-road and on high mountain roads than the MRAP, but is still too heavy to be carried by helicopters, specifically the Army's CH-47 or the Marine Corps' CH-53. By the end of 2010, approximately 8,000 M-ATVs were produced (GAO, 2010, p. 3).

The size and weight of the MRAP vehicles are both a logistical burden and prevent the vehicles from operating on high altitude rugged terrain like that found in Afghanistan. In 2005 the services identified the need for a new generation of lightweight tactical wheeled vehicles to replace the aging HMMWVs. As the IED threat became more pronounced in 2007, a requirement was added that the new vehicles have the armor protection of the MRAP, but weigh much less and be able to replace the HMMWV for many tactical missions. Work on the Joint Light Tactical Vehicle (JLTV) began in 2005, with an anticipated procurement date of 2015. The U.S. Army and Marine Corps are planning to jointly purchase an expected 60,000 JLTVs (GAO, 2011, p. 31). The JLTV and the M-ATV are both light tactical wheeled vehicles that serve very similar roles and are capable of completing many of the same missions. The similarities between the two vehicles open the services to criticism about the level of unplanned duplication in acquisition programs, and if money can be saved by purchasing more or less of one or the other vehicles.

This thesis builds an optimization decision model that takes into account the capabilities of the two types of vehicles, JLTVs and M-ATVs, to determine the optimum ratio of the two vehicles that the Army and Marine Corps can purchase in order to minimize costs.

# II. LITERATURE REVIEW

## A. OVERVIEW

The Mine Resistant Ambush Protected All-Terrain Vehicle (M-ATV) and the Joint Light Tactical Vehicle (JLTV) are light tactical wheeled vehicles (LTWV) currently being procured by the Department of Defense (DoD). The M-ATV is a member of the Mine Resistant Ambush Protected (MRAP) Family of Vehicles (FoV). It was rapidly procured and sent to troops in Afghanistan in 2009 to meet the Improvised Explosive Device (IED) threat that the High Mobility Multipurpose Wheeled Vehicle (HMMWV) cannot meet, but the vehicle is very heavy. In 2005, planning for the JLTV began. The JLTV is being developed to offer the same level of protection provided by the MRAP FoV, while maintaining a lighter weight, similar to that of the HMMWV. Both vehicles, the M-ATV and the JLTV, represent huge expenditures of up to $12.5 billion and $18.5 billion, respectively, but share many duplicative capabilities (GAO, 2011, p. 31). Several studies focus on the need to reduce duplication, develop a DoD Tactical Wheeled Vehicle (TWV) strategy, recapitalize the HMMWV fleet, and the acquisition structure. This chapter reviews these studies and highlights the most important issues that have been considered, as they relate to this thesis.

## B. REDUCE DUPLICATION

Among the primary concerns of the U.S. Government Accountability Office (GAO) is unplanned duplication that would result in billions of additional dollars spent for the same capability. As the GAO writes in 2011: “DoD’s acquisition of two similar tactical wheeled vehicles—the Mine Resistant Ambush Protected vehicle, including an all-terrain variant, and eventually the Joint Light Tactical Vehicle—creates a risk of unplanned overlap in capabilities that could increase acquisition costs significantly” (p. 31). The GAO (2010) is not advocating the use of one vehicle over the other. It rather advocates a measured approach to determine where areas of overlap can be avoided and procurement numbers can be reduced. “Any potential offsets between the MRAP vehicles and JLTVs, to the extent they are supported by cost-benefit analyses, could save both acquisition and support costs" (abstract paragraph 3). *Defense Industry Daily* also recognized duplications between the M-ATV and several other TWVs. On May 30, 2012, the *Defense Industry Daily* writes:

> Oshkosh's design bore many visual similarities to their JLTV TD Phase entry, but without the high-end systems like a hybrid drive, which would have required further development. The core of the vehicle is the U.S. Marines' MTVR medium truck chassis, and its TAK-4 suspension. TAK-4 is being used to refit Cougar MRAPs, and already exceeds M-ATV's off road specifications by offering a 70% off road mobility profile (M-ATV specs: 50%), with more than 16 inches of independent wheel travel. An Oshkosh representative told DID that "generally speaking [TAK-4] will increase the speed of the vehicle by 1.5–2.5 times over the speed of the same vehicle with a straight axle suspension, without sacrificing ride quality. The vehicle's C7 engine is also broadly common to other vehicles, and was used in more than 18,000 vehicles fielded in Iraq and Afghanistan at the time of the award. (paragraph 2)

*Defense Industry Daily* recognizes these duplications in a positive light, but it is easy to identify why some observers would be concerned that the DoD is procuring multiple versions of similarly capable vehicles.

The GAO is concerned that the DoD is focusing on the procurement of JLTV to meet the needs of the war fighter, and only views the MRAP FoV as a stop-gap measure to fill the existing need until JLTV is fielded. As the GAO (2011) states:

> To date, the services have not considered using the vehicles in the Mine Resistant Ambush Protected family—with the exception of some vehicles planned for use by route clearance, explosives ordnance disposal, and medical evacuation units—to offset the need for or replace other tactical wheeled vehicles. Currently, the services consider Mine Resistant Ambush Protected vehicles to be mainly additive to their fleets. Given the high potential cost of the Joint Light Tactical Vehicle, reducing the number of units acquired could offer substantial savings, albeit with potential performance tradeoffs. To illustrate, a 5 percent reduction in Joint Light Tactical Vehicle quantities could save nearly $2.5 billion, assuming a unit cost of $800,000. (p. 31)

Those who meet the GAO's recommendations with skepticism should take comfort that the GAO recognizes the JLTV is not a copy or duplication of any existing vehicle, and that it will bring capabilities to the war fighter that other vehicles cannot.

According to the GAO (2011): “JLTV is being designed to protect its occupants from the effects of mines and improvised explosive devices without sacrificing its payload capability or its automotive performance, which has not been the case with the other tactical wheeled vehicles” (p. 4). This is an acknowledgment by the GAO of the JLTVs usefulness in the TWV fleet. The GAO (2010) also acknowledges the DoD’s efforts to improve efficiency and reduce duplication. As the GAO observes:

> In addition, the Secretary of Defense has recently announced several initiatives to free-up funds for modernization and to create efficiencies in programs. This is a contingency that may also have an influence on the DoD-wide strategy by reinforcing the need to minimize the potential for unplanned overlap or duplication (p. 23).

This thesis recognizes the importance placed on avoiding duplication. Therefore, it proposes a decision model that can address the duplication by incorporating in the cost-minimization decision process a distinct rating system of the capabilities of each vehicle, the M-ATVs and the JLTVs. Details are presented in Chapter IV.

## C. TWV STRATEGIES

The GAO contends that building a DoD-wide TWV strategy is the best way to identify the needs the DoD intends to meet with future TWV acquisitions while avoiding unplanned duplication. Erwin (2011) echoes this argument while highlighting the complexity of pursing multiple urgently needed TWV strategies while avoiding duplication. The U.S. Department of the Army (Army) recently updated its TWV strategy and the U.S. Department of the Navy’s United States Marine Corps (Marines) has done the same, but the DoD is still creating the comprehensive DoD strategy.

The GAO recognized the need for a comprehensive DoD strategy to reduce the risk of duplication. The GAO (2011) points out: “Since 2008, GAO has identified tactical wheeled vehicle procurement as being at risk for duplication, and in 2009 GAO recommended that DoD develop a unified acquisition strategy” (p. 31). The GAO contends the strategy should be all encompassing and recognizes the complexity of such a strategy. The GAO (2011) also continues: “DoD could save both acquisition and support costs through a department wide tactical wheeled vehicle strategy that considers costs and benefits of the Joint Light Tactical Vehicle compared to other tactical wheeled vehicle options" (p. 32).

The GAO (2011) views the need for a DoD TWV strategy as paramount. The GAO points out: "DoD does not have a unified tactical wheeled vehicle strategy that considers timing, capabilities, affordability, and sustainability. DoD stated in 2009 that it would create a unified plan for tactical wheeled vehicle investment decisions" (p. 31–32). The GAO (2010) continues, "as of September 2010, DoD has not yet set a timetable for completing the strategy. In recommending such a strategy and implementation plan in 2009, we noted that the DoD should

- assess and prioritize the capabilities and requirements of similar vehicles needed in the near and long term;
- estimate the funding, time, and technologies that will be required to acquire, improve, and sustain these systems;
- balance protection, payload, and performance needs with available resources, especially for light tactical vehicles; and
- identify contingencies in case there are development problems, delays with key systems, or funding constraints" (p. 23).

While the GAO has been consistent about the need for a DoD TWV strategy, it credits the services for updating their respective TWV strategies and relies on those strategies to ensure the services are procuring vehicles that are in keeping with their stated plans. The GAO (2012) points out: "The Army and Marine Corps updated their individual tactical wheeled vehicle strategies in January 2011 and June 2011, respectively" (p. 4). The GAO (2010) continues: "Both services have also acknowledged that planning uncertainties included JLTV cost and performance, and emphasize the need for the adoption of TWV strategies that are affordable as a whole" (p. 20). GAO acknowledges the services' strategies are mindful of the need for fiscally conservative plans as defense budgets are reduced. The GAO (2010) points out:

> The Army strategy states that in an era of constrained financial support and ever-increasing materiel costs, it will work to control cost growth and variant complexity within the TWV fleet. The Marine Corps strategy

> states that the underlying guidance for the strategy requires the fielding of an affordable fleet of ground combat and tactical vehicles that provide required capabilities and adequate capacity (p. 20).

Regarding the M-ATV and JLTV, the GAO (2010) finds that the services are in compliance with their strategies. The GAO states:

> The acquisition plans for both the M-ATV and JLTV are consistent with the services' TWV strategies, which emphasize maintaining a balance of performance, payload, and protection capabilities across their TWV fleets as they continue to adjust to the improvised explosive devices/roadside bomb threats. M-ATV fulfills a short-term, joint, urgent operational need in support of current operations and JLTV is the long-term solution for the joint services to replace the HMMWV" (p. 19).

The Army and the Marines have continued to update their TWV strategies as new threats emerge, but they maintain continuity where appropriate.

"The Army's October 2009 strategy reiterated that the 2008 Army and Marine Corps joint TWV investment strategy was based on four tenets:

- Take maximum advantage of existing platforms by recapitalizing their platforms and introducing product improvements.
- Plan for the integration of MRAP vehicles into the fleet mixes.
- Emphasize a mixed fleet approach that spans the "iron triangle" of protection, payload, and performance.
- Transition to a fleet of tactical vehicles that have scalable protection (integrated A-kit and add-on-armor B kits)" (U.S. Government Accountability Office, 2010, p. 19–20).

The latest Army TWV strategy continues to evolve to include a possible long term role for the M-ATV, but does not definitively state if the JLTV will replace the M-ATV or if they will complement each other. The Army states: "A large portion of the MRAP FoVs, including the MRAP All-Terrain Vehicle (M-ATV), will supplement the LTV requirements either as a bridge to fill critical combat roles (until the JLTV is fully fielded and/or the remainder of the MRAP FoV EUL), or as permanent enduring capabilities" (U.S. Department of the Army, 2010, p. 8). While the Army's TWV strategy is somewhat vaguely worded about the future of the M-ATV, the Army and the Marines are more optimistic about expanding the future roles of the JLTV. GAO (2011) points out: “As a part of DoD’s planned analysis of alternatives to the Joint Light Tactical Vehicle, the Army and Marine Corps have stated they will explore the implications, including maintenance and life cycle cost benefits, of acquiring a Joint Light Tactical Vehicle family of vehicles as a part of a mixed vehicle fleet” (p. 33).

Erwin, a columnist for National Defense magazine, echoes many of the arguments made by the GAO about the need for a comprehensive DoD TWV strategy: “In deliberations over how to modernize the fleet, the $36 billion already poured into MRAP is the elephant in the room. That equates to almost half the value of the entire $70 billion Army fleet of 266,000 trucks” (2011, paragraph 5). Erwin is critical about the services’ inability to decide if the M-ATV will remain in the TWV fleet or if it will be replaced. “The services have yet to offer details on whether MRAP will become a “program of record” that will stay permanently in the inventory after current wars are over” (paragraph 6). She points to multiple TWV programs currently being funded as part of the problem:

> Discussions over how to move forward have been paralyzed by the fact that there are so many programs—JLTV, MRAP, the MRAP all-terrain vehicle, a next-generation Marine Corps personnel carrier, new production Humvees and upgrades for Humvees—that are competing for the same light tactical vehicle mission role. “That’s what’s got people unable to make decisions,” the industry source says (paragraph 9).

She fears that the decreasing defense budget could result in the JLTV program being canceled, and says “The speculation is that MRAPs, or possibly the lighter “all-terrain” variant, could end up crushing JLTV in future budget drills” (paragraph 6).

The Army’s latest TWV strategy is ambiguous about how important a role the M-ATV will play, but a reader could understand why some may fear a decreasing budget would result in the JLTV program being canceled. Some of the statements in the Army’s TWV strategy include “MRAP FoV integrated into the Army force structure to take advantage of existing systems to meet documented requirements and to reduce operating costs by divestment of duplicative systems” (U.S. Department of the Army, 2010, p. 4) and “shape TWV fleet size and mix to ensure long-term affordability through new procurement, recapitalization and divestment; leverage existing assets to the greatest extent" (U.S. Department of the Army, 2010, p. 5). As a part of the existing assets the Army plans to leverage, it is important to note the Army already has thousands of M-ATVs. As Erwin (2011) writes: "As of June 2010, the Army had more than 19,800 M-ATV and MRAP vehicles in overseas war zones and in the United States. The Marine Corps has a combined MRAP and M-ATV fleet of about 3,300 vehicles" (paragraph 22).

## D. RECAPITALIZATION

Many recommendations and proposals for how to modernize the TWV fleet include recapitalizing the existing HMMWV fleet. Feickert, a specialist in military ground vehicles for the Congressional Research Service, examines this point in detail weighing both the pros and cons. While the JLTV is designed to replace the HMMWV the DoD does not see a requirement to replace all of the existing HMMWVs. Feickert (2012) notes: "DoD officials have emphasized that JLTVs are not intended to replace HMMWVs "one for one" (p. 1).

Recapitalization involves refitting and modernizing an existing vehicle to essentially bring its mileage back to zero and renewing its useful life. It is a cost effective method of updating the TWV fleet. GAO (2010) points out: "Begun in 2004, approximately 30,000 vehicles have been recapitalized at a cost of approximately 35 percent of the value of a new production light-utility vehicle" (p. 20). However, modernizing HMMWVs to meet the existing need may be impossible. Feickert (2012) notes: "The Army contends that adding additional armor puts significant stress on engine, suspension and transmission equipment, requiring extensive and costly modification to these vehicles" (p. 11).

While recapitalizing HMMWVs is cheaper than buying new vehicles, the services are anticipating the per-unit cost of the JLTV to be similar to the cost of recapitalizing HMMWVs. Feickert (2012) makes the point:

> With the proposed target cost for the JLTV in the $230,000-$270,000 range, some defense officials suggest that the JLTV could reach cost parity with recapitalized HMMWVs. The Marine Corps is reportedly not releasing a Request for Proposal (RFP) for HMMWV recapitalization (recap) noting that:

> When you start trying to bring those capabilities back into the [HMMWV] recap, your price goes up to the $240,000 to $250,000 range, and now you're at [the price of] a JLTV vehicle, which has so much more payload and so much more capability.
>
> Army program officials contend that some recapitalized HMMWV versions could cost as much as $500,000 per vehicle. Analysts also suggest that a new JLTV will have a much greater operational life than a "used" recapitalized HMMWV. Given these considerations, Congress might decide to further examine how the new proposed target cost for the JLTV in the $230,000- $270,000 range affects current and future HMMWV recapitalization efforts." (p. 11)

Given this information, congressional officials began to wonder if recapitalization efforts for the HMMWV are worth the expense. One Army recapitalization program was denied by Congress, which seemed to indicate Congress was no longer willing to fund recapitalization efforts. "Because the Army's requested reprogramming action has been denied by the Congress, all recapitalization plans have been suspended pending the development of revised plans for the HMMWV production and recapitalization programs" (U.S. Government Accountability Office, 2010, pp. 20–21). Following that announcement, Army officials decided to cancel other recapitalization efforts as well. Beidel, a columnist for National Defense Magazine, notes: "The Army recently announced the termination of a program to recapitalize a portion of the Humvee fleet that would have covered about 6,000 trucks" (2012, paragraph 3). This was a clear sign that DoD officials now intended to replace HMMWVs with JLTVs to the fullest extent possible. In Beidel's words, Defense Department officials "are throwing their support behind the Joint Light Tactical Vehicle as a replacement for the trucks, some of which have been in service since the 1980s" (2012, paragraph 2).

## E. LONG-TERM FUNDING

The availability of long-term funding is the key to keeping any acquisition program alive. Many factors are involved in deciding to fund an acquisition program like the JLTV, and these areas are addressed in detail by the GAO (2011), Erwin (2011), Feickert (2012), and Goodman (2011) who is the senior editor of the Journal of Electronic Defense.

One of the major difficulties is predicting a unit cost. The Army has been fairly consistent in expecting the JLTV unit cost to be about $300,000. “The cost per vehicle is not yet determined, but it is expected to exceed $300 thousand without the inclusion of mission equipment” (U.S. Department of the Army, 2010, p. 7). The Army attempts to soften the blow of such a high cost by comparing it to a similar vehicle. “It is estimated that each JLTV will cost in excess of $300 thousand before equipping with essential combat systems—but not as high as the cost of the MRAP Family of Vehicles (FoV) which cost $430–$900 thousand apiece to procure” (U.S. Department of the Army, 2010, p. 3).

Erwin (2011) points out that predicting a unit cost depends on what you include in that cost. Some estimates include only the vehicle, while others include the necessary vehicle equipment. Referencing GAO’s Michael J. Sullivan, Erwin claims:

> Production funding is currently projected to start in fiscal year 2013. Through fiscal year 2015, the services are predicting they will need $2.7 billion for JLTV procurement. The program’s total acquisition costs could be substantial, he said. The target unit-production cost ranges from $306,000 to $332,000, depending on vehicle category. That compares to the base M-ATV unit price of about $445,000. Armor kits and mission equipment packages are additional. As a reference point, the cost of government-furnished equipment averaged $532,000 per vehicle for the M-ATVs. If similar costs apply to JLTV, its procurement unit cost could be in excess of $800,000, GAO estimated (paragraph 18).

The GAO (2011) expects the total acquisition cost of the JLTV to exceed $18.5 billion. “While acquisition costs for the Joint Light Tactical Vehicle are yet to be determined, a low-end estimate is $18.5 billion. The cost per unit, including mission equipment, could be over $800,000 each” (p. 31).

Long-term funding must consider the cost of the vehicle over its whole life, including recapitalization. For a comparison on the cost of recapitalization, the Army compares it to the rest of its TWV fleet. “The annualized cost to replace each of our current vehicles every 40 years, with a recapitalization performed mid-way, is over $2 billion/year and over $2.5 billion/year if MRAPs are included. If the Army were to replace all HMMWVs with JLTVs, this would add over $2–$5 billion/year to these estimates, depending on the procurement rate" (U.S. Department of the Army, 2010, p. 4).

When speaking about JLTV unit cost, one must also consider M-ATV unit costs. The GAO points out: "The estimated total acquisition cost for the Mine Resistant Ambush Protected All-Terrain Vehicle is about $12.5 billion" (U.S. Government Accountability Office, 2011, p. 31). The life cycle costs of the M-ATV must be considered as well. The GAO also notes: "While the cost to operate and sustain the vehicles [MRAPs] for their expected service life will depend on the military services' specific plans to integrate the vehicles into their force structures, the MRAP joint program office estimates that the cost to operate and maintain the vehicles through 2024 will be about $10.8 billion" (U.S. Government Accountability Office, 2010, pp. 21–22).

Another large factor to consider when deciding to fund an acquisition program is risk. Once a service starts to lose interest in a program due to doubts of the program's possibility of success, it is a clear sign the program is experiencing more risk than the service is willing to accept. Erwin (2011) points to one clear indication; "JLTV has floundered recently, as the Marine Corps soured on the vehicle for being too heavy. Its estimated price tag of nearly half-a-million dollars per truck has made it all that much more certain that if the services end up buying JLTV, it will be in smaller numbers than industry had hoped" (paragraph 4). The GAO identified risk in this same area in a 2010 report. "This category of JLTV vehicles [JLTV Force Application category] is at risk of not meeting the transportability requirement due to their projected weight and the projected requirement for reliability is two to three times greater than other tactical vehicles" (U.S. Government Accountability Office, 2010).

The U.S. Senate Appropriations Committee in 2011 decided the JLTV program was riskier than they were willing to accept. Feickert (2012) explains:

> On September 13, 2011, the Senate Appropriations Defense Subcommittee recommended the termination of JLTV program, noting "excessive cost growth and constantly changing requirements" suggesting that "alternatives exist today to meet the Army and Marine Corps' requirements to recapitalize and competitively upgrade the HMMWV

> fleet." The subcommittee expressed concern that early program cost growth and projected acquisition costs will make the program unaffordable in a challenging economic environment. (p. 5)

In some cases, when an acquisition program is at risk of being canceled, the services find a way to reduce the program risk in order to make it a more attractive investment. Feickert (2012) identifies how the Army and Marines did just that in the case of the JLTV:

> In what has been characterized as a response to the Senate Appropriations Committee recommendation to terminate the JLTV, the Army and Marines apparently put aside past differences and developed a new acquisition strategy that relaxes transportability requirements and sets a goal for a lower per-unit cost of $225,000. The Army notes this lower price tag is a result of requirement trade-offs but crew survivability remains of paramount importance." (p. 5)

This does not mean the JLTV is no longer considered a risky investment. When submitting its budget proposal for fiscal year 2012, the Army included funding that will allow it to take the JLTV into the EMD phase of the acquisition process. Delays in the schedule were considered by the appropriations committee, as Feickert (2012) points out: "The conference recommended reducing the Army's $172.1 million budget request by $64.8 million due to 'schedule slip' (delay of awarding the EMD contract) and reducing the Marines' $71.8 million request by $24.9 million for the same reason" (p. 9). When the Army presented a restructured schedule that would allow for a fast acquisition process, the conference responded again. "Recognizing the renewed focus and approach, the conference agreement provides $87,300,000 in Research, Development, Test and Evaluation, Army and $46,700,000 in Research, Development, Test and Evaluation, Navy for continued JLTV development, in accordance with revised estimates for the program" (Feickert, 2012, p. 9).

Investing in acquisition programs like the JLTV requires enormous resources. When deciding to invest in a program, the services are also deciding to not invest in other programs. The smaller the pool of resources becomes, the more difficult the decisions become. Feickert (2012) identifies how the Marines plan to deal with the threat of budget reductions:

> Marine leaders reportedly testified to the House Armed Services Subcommittee on Tactical Air and Land Forces on November 16, 2011, that if significant budget cuts are enacted due to sequestration of the defense budget under the provisions of the Budget Control Act of 2011, P.L. 112–25, the Marines would defer acquisition of the JLTV until the late 2020s. The Marines would instead develop and procure the Amphibious Combat Vehicle (ACV) before acquiring any JLTVs. Experts suggest that if the Marines defer until the late 2020s that the per vehicle cost for the Army's JLTVs—that it hopes to begin procuring in 2015—would increase and possibly endanger the overall program. (p. 6)

The threat of drastically shrinking budgets has spurred many studies about how to deal with the reduced resources. Feickert (2012) finds another example of how the JLTV may end up on the chopping block:

> A number of think tanks and commissions—including the presidentially-appointed Bowles-Simpson Fiscal Commission37—who are proposing ways to decrease DoD spending have recommended the JLTV program be cancelled or deferred. Given this wide-ranging opposition to the JLTV program on the basis of affordability, even a $230,000 per copy JLTV variant might prove to be difficult to justify." (p. 10)

Even if defense budgets remain unaffected by the Budget Control Act of 2011, the Marines recognize that the cost of the JLTV means they cannot have as many as they want. The GAO points out: "Marine Corps officials acknowledged that the projected cost to sustain their tactical vehicle fleet contributed to a decision to reduce the quantities of tactical vehicles by 30 percent over the next few years" (2010, p. 22).

## F. CAPABILITIES

To understand the complexity of these vehicles, and why they cost so much, we must understand what the M-ATV and JLTV are capable of, and what they are expected to do. Many requirements on the JLTV in particular constrain each other. For example, it must be able to have high enough ground clearance to perform well off-road, but must be short enough to fit inside the Navy's amphibious ships. They must be light enough to be carried by helicopters, but have enough armor protection to allow the passengers to survive an IED blast. This section looks at the capabilities of the two vehicles and the challenges they pose.

The most difficult technical problem the JLTV needs to overcome is weight. Erwin (2011) offers a comparison of three TWVs: “An M-ATV weighs 32,500 pounds, compared to 12,000 to 15,000 pounds for a Humvee and about 20,000 to 24,000 for JLTV” (paragraph 17). The weight of the M-ATV means it is not capable of doing some of the things the JLTV is required to be able to do. The JLTVs weight is taking its toll as well. Feickert (2012) illustrates how the weight of the vehicle is causing the program to be scaled back: “The Category B variant was eliminated because it proved to be too heavy to meet the required weight of approximately 15,639 pounds to make it transportable by Army CH-47F and Marine Corps CH-53K helicopters” (p. 3). “Originally, there were three variants, but now there are two planned JLTV variants: a four-passenger Combat Tactical Vehicle (CTV) and a two-passenger Combat Support Vehicle CSV)” (p. 1).

Related to the JLTVs weight is its armor protection capabilities. The JLTV is designed to have MRAP-like armor protection. Goodman (2011) explains how the JLTV demonstrated this capability during the TD phase of the acquisition process:

> The services completed all planned performance and RAM testing; however, because of the increased requirement in under-body survivability, more challenging ballistic testing was conducted to help inform the Engineering and Manufacturing Development (EMD) phase requirements. Additionally, JLTV’s first helicopter sling load transportability test with the Army’s CH-47D and the USMC’s CH-53E was completed with General Purpose, four-passenger vehicles. (paragraph 3).

The JLTV will have the ability to operate with less armor when the situation allows, and be able to bolt on more armor when necessary. Goodman (2011) continues:

> The JLTV will feature inherent and B-kit scalable armor. The vehicle’s inherent armor protection levels, sufficient for non-combat humanitarian operations, will be supplemented by the addition of bolt-on B-kit armor for enhanced protection on combat missions. All three industry teams are using modular B-kit armor panels made of advanced lightweight composite materials instead of metal to keep weight down while providing ballistic, mine, and IED protection. (Crew Protection Imperative, paragraph. 2)

Still, armor protection is one area where it is difficult to find a good balance. As the enemy increases its capabilities, the Army reacts. Feickert (2012) notes: “In February 2011, the JLTV Program Office announced that the award of the EMD contract would be delayed until January or February 2012 because the Army changed requirements for the JLTV to have the same level of under body protection as the Mine-Resistant, Ambush-Protected All-Terrain Vehicle (M-ATV)” (p. 3).

Armor protection is the nemesis of a vehicle with a weight requirement. Even without the weight requirement, heavy vehicles experience reduced performance. Goodman (2011) explains how weight killed the HMMWV:

> Up-armoring of HMMWVs through the addition of armor plates provided increased protection, but the increased weight reduced the vehicle’s payload capacity, maneuverability, off-road mobility, and air transportability. With the JLTV, the Army and Marine Corps hope to regain the performance once offered by the HMMWV while adding inherent crew protection against IED-like threats. (Crew Protection Imperative, paragraph 1)

The JLTV will experience increased performance in other areas as well. Goodman (2011) details the JLTVs performance:

> The JLTVs also improve payload efficiency through chassis engineering, enabling the vehicles to be deployed with the appropriate amount of force protection through scalable armor solutions. Further, expected JLTV fleet reliability and fuel efficiency will be significantly greater than the current HMMWV fleet, which will reap millions of dollars in savings over the JLTV life cycle. (paragraph 6)

Beyond automotive capability, the JLTV will have features that no other combat tactical vehicles currently have. Goodman (2011) explains the electronics package:

> The JLTV will feature an open electronics architecture that will facilitate integration of future sensor, communications, and navigation systems as they become available. As a result, the JLTV’s crew will have significantly improved battlefield situational awareness compared with vehicles today. (Vehicle Configurations, paragraph 4)

## G. ACQUISITION STRUCTURE

Before the JLTV can start benefitting the war-fighter, it must successfully complete the acquisition process. Feickert (2012), Goodman (2011), and John-Givens (2012) who is a strategic communications officer for the Program Executive Office, Combat Support and Combat Service Support, track the JLTV through the acquisition phases and milestones. Feickert (2012) gives a quick overview:

> The JLTV is an Acquisition Category (ACAT) 1D program. The Army bears the overall responsibility for developing the JLTV through its Joint Program Office within the Army’s Tank, Automotive, and Armament Command (TACOM) in Warren, MI. Marine participation is centered on a program office under the supervision of the Program Executive Officer Land Systems (PEO LS) Marine Corps at Quantico, VA. (p. 1–2)

The most recent phase the JLTV completed was the Technology Development phase. Successful completion of this phase was critical to reaching milestone B. John-Givens (2012) describes the JLTVs progress:

> In the spring of 2011, JLTV successfully completed a 27-month Technology Development, or TD, phase -- satisfying its intended purpose of demonstrating the integration of mature technologies as a complete system and providing the Army and the Marine Corps with an assessment of the technical, performance cost and schedule risks relevant to entering the Engineering and Manufacturing Development, or EMD, Phase. (paragraph 6)

Goodman (2011) supplements the progress and looks toward the next phase:

> The TD phase has satisfied its intended purposes: demonstrate the integration of mature technologies as a complete system and provide an assessment of the technical and performance risks relevant to entering the EMD phase. The EMD phase will be a full and open competition, with the selection of multiple offers. Milestone B is currently scheduled for 2nd quarter of FY 12. (paragraph 7)

Looking toward the next phase, the Army is prepared to request proposals from industry. Feickert (2012) notes:

"On October 3, 2011, the Army issued a draft Request for Proposal (RFP) for the Engineering and Manufacturing Development (EMD) phase. Key provisions include

- a $230,000 to $270,000 per vehicle cost target;
- an additional add-on armor kit (called a B kit) can cost no more than $50,000;
- EMD phase cut by 16 months—will now be 32 versus 48 months; and
- Army intends to procure at least 20,000 JLTVs with options to procure more." (p. 6)

In order to insure the JTLV completes the acquisition process in a timely manner, officials have restructured the EMD phase and shortened the total time requirement. "The refined 27-month acquisition strategy is designed to put a premium on driving down costs, reducing risk and getting vehicles into the hands of warfighters quickly. The JLTV EMD contract period of performance for contractors is 27-months, while the full EMD phase will last for 33-months as the program offices ensures JLTV moves successfully from Milestone B to Milestone C" (John-Givens, 2012, paragraph 9). To facilitate the award of EMD contracts, the Army must have the budget authority to pay for such contracts. With this knowledge in mind, Feickert (2012) demonstrates the Army is ready to move forward:

> The FY2012 Budget Request for JLTVs is $172.1 million for Army Research, Development, Test and Evaluation (RDT&E) and $71.8 million for Marine Corps RDT&E, for a program total of $243.9 million. The significant increase from the FY2011 Budget Request of $84.7 million reflects the anticipated award of the EMD contracts in January or February 2012. (p. 9)

The Army expects to build the first production model JLTVs in fiscal year 2015. "The Low Rate Initial Production of the JLTV is expected to start no earlier than FY15" (U.S. Department of the Army, 2010, p. 7).

## H. CHAPTER SUMMARY

This chapter provides a review of the studies addressing the issues around the acquisition of the JLTV and the M-ATV. It provides the reader with the background knowledge necessary to better understand the approach taken in this thesis and to interpret the results. The next chapter details the methodology used in this thesis to identify the optimum ratio of the two vehicles to be purchased to minimize costs while considering the vehicles' specific capabilities.

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# III. METHODOLOGY

## A. OVERVIEW

This thesis builds an optimization decision model that can be used to determine the optimum ratio of JLTVs and M-ATVs the Army and Marine Corps can purchase to minimize costs while taking into account all the constraints related to each vehicle's capabilities, required off-road capabilities and transport ease for missions supported by the services. In this thesis, the "optimum" ratio is the ratio that best meets the needs of the services while minimizing production costs. The JLTV and M-ATV are wheeled tactical vehicles that share many capabilities and play very similar roles. The level of duplication in the capabilities of these vehicles leads to questions if the redundancy can be limited in order to save cost.

This thesis uses a non-linear programming optimization decision model to achieve an optimum ratio of the two vehicles. The methodology behind the non-linear programming optimization model proposed in this thesis is described below.

## B. DECISION MODELING

Non-linear programming optimization decision models are a type of mathematical programming, part of a larger practice called decision modeling. The Render, Stair and Balakrishnan textbook, "Managerial Decision Modeling With Spreadsheets," defines decision modeling as "a scientific approach to managerial decision making" (2003, p. 3). Using a systematic scientific approach and mathematical tools to solve decision problems minimizes bias and guesswork in finding the solution to decision problems.

Mathematical programming is the most widely used decision modeling technique. It is used to identify the optimum choice amongst potentially thousands of decision possibilities. Mathematical programming usually deals with identifying the optimum allocation of limited resources, subject to various constraints.

In general, decision models are categorized into two types, deterministic and probabilistic models, based on whether the data used in the decision making process is known with certainty or not. Deterministic models, as described by Render et al. (2003), "assume that all the relevant input data are known with certainty; that is, they assume that all the information needed for modeling the decision-making problem environment is available, with fixed and known values" (p. 5). For probabilistic models, not all the data used in the decision model are known with certainty. Defined by Render et al. (2003), "probabilistic models assume that some input data are not known with certainty. That is they assume that the values of some input variables will not be known before decisions are made" (p. 5).

The data used in this thesis is not processed using probabilities; therefore the type of decision model this thesis utilizes is a deterministic model. However, uncertainty can be incorporated into the decision model. This thesis addresses some potential for uncertainty by conducting sensitivity analysis, as described in detail in Chapter V.

## C. MATHEMATICAL PROGRAMMING COMPONENTS

There are four components to a mathematical programming decision model, described below.

### 1. The Decision Variables

The decision variables are the variables that are adjusted within the model in order to determine the optimal solution. Decision models answer questions such as "how many" and "what is the cost (or profit) value considering the values of the decision variables in the optimum solution" Decision variables typically answer the "how many" question. For example, if product A sells for $100, and it requires 1 hour of machine time, and product B sells for $200, and requires 1.5 hours of machine time, how many of product A and how many of product B should the producer make in order to minimize cost (or maximize profit )? In this example, A and B are the decision variables, as they answer the question: "how many?"

### 2. The Objective Function

The objective function is the mathematically expressed component of the model that seeks to maximize or minimize some quantity. Render et al. (2003) describe objective functions very clearly.

> All problems seek to maximize or minimize some quantity, usually profit or cost. We refer to this property as the objective function. For example, the objective of a typical manufacture is to maximize profits. In the case of a trucking or railroad distribution system, the objective might be to minimize shipping costs. In any event, this objective must be stated clearly and defined mathematically. (p. 26)

Profits and costs are determined by incorporating a mathematical function of the decision variables. The function is linear in decision variables for what are called "linear programming models," and non-linear in decision variables for so-classed "non-linear programming models."

As an example, total costs from combined production of A and B = (cost per unit A* number of units A + cost per unit B* number of units B).

The cost per unit A and B, respectively, are the coefficients of the objective function in this example, using a cost minimization objective function .The objective function used in the model developed in this thesis is non-linear. Details are provided in Chapter IV.

### 3. The Constraints

The constraints are the restrictions within which the model must operate. Render et al. (2003) explain constraints as follows:

> LP models usually contain restrictions, or constraints, that limit the degree to which we can pursue our objective. For example, when we are trying to decide how many units to produce of each product in a firm's line, we are restricted by the available machinery time. Likewise, in selecting food items for a hospital meal, a dietitian must ensure that minimum daily requirements of vitamins, proteins, and so on are satisfied. We want, therefore, to maximize or minimize a quantity (the objective) subject to limited resources (the constraints) (p. 26).

The constraints are typically expressed mathematically as linear functions of decision variables. This is also the case for the constraints incorporated in the model built in this thesis.

### 4. The Optimum Solution

The optimum solution is the set of values the decision variables take to insure the optimization of the objective function while satisfying the constraints of the model. In a cost minimization model, the optimum solution is the set of values for each decision variable that minimize total costs while meeting the constraints of the available resources.

The size and scope of mathematical programming problems require the use of computer applications to identify the optimum solution to any optimization problem. This thesis uses Microsoft Excel's Solver add-in package to implement the decision model and to identify the numerical optimum solution to the optimization problem.

## D. STEPS IN CONDUCTING MATHEMATICAL PROGRAMMING ANALYSIS

Mathematical programming analysis, as described by Render et al. (2003), is broken into three distinct steps: formulation, solution, interpretation and sensitivity analysis, addressing "what if" questions to ensure robustness of the solution and recommendations based on the solutions.

### 1. Formulation

The formulation phase is the process of using mathematical formulas to frame the problem. Render et al. (2003) explain, "Formulation is the process by which each aspect of the problem scenario is translated and expressed in terms of simple mathematical expressions, taken together, completely addresses all the issues relevant to the problem situation at hand (p. 26)" Specifically, the formulation includes the definition and mathematical formulation of the decision variables, of the objective function, and of the constraints.

### 2. Solution

The solution phase identifies the optimum solution that optimizes the objective function while satisfying the constraints. Given the size and computational complexity of most optimization decision models, computer programs are generally used to implement the mathematical model and to identify the solution of the model. This thesis uses Microsoft Excel's Solver add-in package for academic use.

### 3. Interpretation and Sensitivity Analysis

The interpretation and sensitivity analysis phase allows the user to interpret the results and understand how changes in the input data would affect the results. Render et al. (2003) explain:

> Assuming the formulation is correct and has been successfully implemented and solved using an LP software package, how does a manager use the results? In addition to just providing the solution to the current LP problem, the computer results also allow the manager to evaluate the impact of several different types of what-if questions regarding the problem (p. 26)

Sensitivity analysis asks "What if" questions that enable the user to understand how the optimum solution of the model changes if any one given data used in the model changes. Sensitivity analysis is particularly important for validating the recommendation based on the optimum solution of the optimization model. By conducting sensitivity analysis, the decision maker checks the robustness of the optimum results of the optimization model, and, therefore, the robustness of the recommendation made based on the results of the optimization model.

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# IV. THE MODEL

This chapter details the main elements of the non-linear programming optimization model used in this thesis to identify the optimum number of M-ATVs and JLTVs to be procured to minimize costs while taking into account a host of constraints related to the two vehicles capabilities.

## A. DECISION VARIABLES

There are two decision variables in this thesis's model. The first is the quantity of JLTVs the Army and Marine Corps could procure; the second is the quantity of M-ATVs the Army and Marine Corps could procure. The goal of this model is to identify the optimum ratio of JLTVs and M-ATVs the Army and Marine Corps could procure.

## B. OBJECTIVE FUNCTION

The objective function in this thesis is designed to minimize the combined procurement costs of the JLTV and the M-ATV. This model is a cost minimization decision programming model. The mathematical formula that describes the objective function used is as follows:

> Minimum Production Cost = (Cumulative Average Cost JLTV * # JLTV Produced) + (Cumulative Average Cost M-ATV * # M-ATV Produced)

The objective function contains cumulative average costs for both, the JLTV and the M-ATV. The cumulative average cost per vehicle is not a parameter of a given value, but rather a function of the number of vehicles produced. Specifically, as the quantity of vehicles increases, the average unit cost decreases due to the learning curve.

Learning Curve Theory originated in the 1920s in the aircraft industry, and can be referred to by many other names. The Defense Acquisition University lists the common names for Learning Curve Theory as experience curve, cost curve, or cost improvement curve. Learning curve theory is well explained by the Defense Acquisition University (DAU) publication BCF106 Fundamentals of Cost Analysis. The following quote explains the basic concept of learning curve theory, and is taken form BCF106:

> The general learning curve theory states that as the number of units produced doubles, the unit cost decreases in a predictable pattern. It is generally accepted that when a new task is undertaken, you learn while actually performing the task. The more often the task is repeated, the more efficient you become at performing the task, and the time required to perform the task decreases. Whether we are speaking of time or money, this means that each unit costs less than the preceding unit.

The idea behind Learning Curve Theory is that the greater the quantity of something that an organization produces, the less expensive it becomes to produce each subsequent unit. It is believed that workers and managers become better at producing the product, while tooling and production methods improve as well. BCF106 credits the first publication utilizing learning curve research to T.P. Wright in 1936 in the Journal of the Aeronautical Sciences, "Factors Affecting the Cost of Airplanes."

Learning curve theory can be used either as unit formulation or cumulative average cost. Unit formulation can be used to estimate the cost a particular unit, for example, the 100th vehicle. Cumulative average cost can be used to estimate the average unit cost of a batch of units, for example, the average unit cost of units 1–100.

The formula for the cumulative average cost is YN = A*N^b where:

YN = the average cost of N units

A = the theoretical cost of the first unit

N = the cumulative number of units produced

b = a constant representing the slope of the learning curve

In this thesis's model, A for the JLTV is $10,000,000 and A for the M-ATV is $8,000,000. These figures were derived using multiple cost estimates that were published in the media (GAO 2010; GAO Testimony, 2011; Erwin, 2011), and then using algebra to solve for A. N for each vehicle is provided by Microsoft Excel's solver program as it searches for the optimum number of each vehicle to produce. The slope, b, for each is –0.321928095, which represents a learning curve slope of 80%. Eighty percent was chosen by the author of this thesis based on the author's understanding of the labor/automation ratio present in the production processes of these vehicles. Actual percentages for these two vehicles were not available to the author, but can be modified by the user of the model as more accurate information becomes available.

Solving the cumulative average cost equations yields the YN of each vehicle. YN then gets multiplied by N to get the total cost of producing N vehicles, and the two are summed up together to get the combined cost of producing N JLTVs and N M-ATVs. This is the optimized result of the objective function. Microsoft Excel's Solver function seeks the optimum N for each vehicle to minimize the total cost.

This thesis becomes a non-linear model because the coefficients in the objective function are raised to powers other than one. Graphically expressed, they both would form curved lines.

Based on the description of the cumulative average cost functions, the mathematical formula that describes the objective function becomes:

> Minimum Production Cost = Cost of first unit of JLTV*# JLTV Produced raised by the slope of learning curve for producing JLTVs) + (Cost of first unit of M-ATVs* # M-ATV Produced squared raised by the slope of learning curve for producing M-ATVs).

## C. CONSTRAINTS

The constraints are entered as mathematical formulas that represent the actual limitations of the scenario being modeled. Typically, the constraints represent resource limitations. The model in this thesis has six constraints. An explanation of the grading and assumptions follow after each constraint and formula, as described below.

Only a positive number of M-ATVs and JLTVs can be produced. This is known as a non-negativity constraint.

Given that a grade on 10 out of 10 is assigned for transportability for the JLTV, and a grade of 5 out of 10 for the M-ATV based on the inability of the M-ATV to be carried by a CH-47 or CH-53 helicopter, the mixture of the two must have a minimum average grade of 7 out of 10. A mix grade of 7 is a starting point. The user of the model can adjust the mix grade to suit their needs. The constraint is expressed as follows:

$3(\#JLTV) - 2(\#M\text{-}ATV) \geq 0$

Given that a grade of 7 out of 10 is assigned for the off-road capability of the JLTV and 5 out of 10 for the M-ATV, the mixture of the two must have a minimum average of grade of 6 out of 10, expressed as follows:

$(\#JLTV) - (\#M\text{-}ATV) \geq 0$

The minimum number of M-ATVs to be produced must be 1, expressed as follows:

$\#M\text{-}ATV \geq 1$

The minimum number of JLTVs to be produced must be 1, expressed as follows:

$\#JLTV \geq 1$

The mixture of vehicles must equal a minimum of 90,000 total units, expressed as follows:

$\#JLTV + \#M\text{-}ATV \geq 90{,}000$

This thesis assigns grades on a scale of 1 to-10, with 10 being the best, to the transportability and off-road capability of these two vehicles. The JLTV is assigned a grade of 10 for transportability because it will be transportable via all methods desired by the Army and Marine Corps. Most importantly, the JLTV will be light enough to be carried by CH-47 and CH-53 helicopters. The M-ATV is too heavy to be transported via helicopter. This significantly degrades the military's ability to quickly move the vehicle from place to place via air. If a vehicle breaks down in a remote combat zone, it is usually safer to fly the vehicle out for repairs than to drive a convoy out to retrieve it. For these reasons, this thesis assigns a grade of 5 to the M-ATV for transportability.

This thesis uses the same 1-to-10 scale to grade the two vehicles on their off-road capability. Both vehicles are designed to perform well on off-highway conditions, but the JLTV's chassis and suspension are receiving additional attention that the M-ATV was not afforded. The considerable weight of both vehicles will still affect their off-road performance, but the JLTV's lighter weight, chassis and suspension improvements should give it an advantage of road over the M-ATV. This thesis assigns a grade of 7 out of 10 to the JLTV and 5 out of 10 to the M-ATV for off-road capability.

The transportability and off-road capability constraints are converted into formulas that yield an average grade. The average grade for transportability is 7 and the average grade for off-road capability is 5. These average grades are used because they split the difference between the two constraints. A future researcher can easily modify the average grades if they feel the average grade of the fleet should be weighted closer to the more capable vehicle, or the less capable vehicle. This thesis shows in Chapter IV how adjusting the average grade affects the optimization model's results.

The quantity of light tactical wheeled vehicles the services expect to procure has changed several times over the past few years and will likely change several more times as the defense budget is reduced and the war in Afghanistan draws down. The actual quantity of vehicles the model proposes to build is set as a minimum number as a constraint. Without this constraint, the cost minimizing model will find it least expensive to build one vehicle that meets or exceeds the minimum grades. In this example, the model would find that building one JLTV is optimum. This thesis sets the minimum number of vehicles at 90,000, which approximates the original expectation of the total quantity of vehicles the services would procure. The quantity of vehicles procured will affect the unit cost of the vehicles and the total cost of purchasing the vehicles. As the quantity decreases the total cost will decrease, but the per-unit costs will increase.

## D. CHAPTER SUMMARY

This model utilized in this thesis uses well-established techniques in the decision modeling and learning theory disciplines to offer a decision tool useful for determining the optimum ratio of M-ATVs and JLTVs the U.S. Army and the Marine Corps can purchase to minimize costs while reducing redundancy and achieving the desired level of capability

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# V. RESULTS AND ANALYSIS

## A. DATA

The results produced by any decision model depend in large part on the data and assumptions built into the model. However, the results are less important than what they teach us about how adjustments in the data affect the results. The model developed in this thesis is meant as a tool for incorporating different scenarios in the decision making process, and to evaluate how each scenario affects decision making.

In this thesis, there are several assumptions made that can be adjusted or manipulated to fit any scenario. First, an assumption is made that the learning curve in the production process for the vehicles is the same for both vehicles. The similarities of the two vehicles indicate the production processes will be very similar. Similar production processes will have similar learning curves. Learning curve percentages are based on production processes, especially the amount of labor involved in the process. The more automated the production process, the higher the learning curve percentage. An 80% learning curve means every time the production quantity is doubled, the average unit cost is reduced by 20%. In this model, it is assumed that there is an 80% learning curve for both vehicles.

The second assumption made is an estimate of the theoretical first unit costs for both vehicles. Using the cumulative average cost formula, algebra, and media estimates about the unit costs and production quantities of each vehicle, the theoretical first unit cost estimates are $10 million for the JLTV and $8 million for the M-ATV.

The final assumptions made were in regard to the assignment of grades to the vehicles. A grading system that is based on a scale of 1-to-10 is used, with 10 being the best. A grade is assigned to each vehicle in the areas of transportability and off-road capability. The critical element that affected the grades in both of these areas is vehicle weight. The JLTV can be transported via CH-47 and CH-53 helicopters. The M-ATV cannot be transported by either of these helicopters because it is too heavy. Media reviews and indications as to how each vehicle fares off road were somewhat based on chassis design, but in the end the lighter vehicle is slightly more agile and capable off road. For transportability, a 10 grade is assigned for the JLTV, and a 5 for the M-ATV. For off-road capability, a 7 grade is assigned for the JLTV, and a 5 for the M-ATV. My model calls for a mix of vehicles that yields an average grade of no lower than 7 for transportability, and no lower than 6 for off-road capability.

Media reports are not consistent on the quantities of vehicles expected to be purchased. As budget debates persist we can expect the quantity of vehicles ordered for production to continue to be adjusted. For the purposes of this thesis, there is a limit the total number of vehicles produced at 90,000 vehicles.

## B. RESULTS

The mathematical model developed in this thesis is implemented in Solver in order to obtain the optimum solution of the model using the Evolutionary solving method to find a good answer, and then using the Generalized Reduced Gradient (GRG) Nonlinear method to find the optimum solution from that point. The model and results are shown in Figure 1.

| | | JLTV | MATV | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| Objective Function | | | | | | |
| | Min Cost | $254,151 | $8,000,000 | $22,881,329,421 | | |
| | | | | | | |
| Contraints | | | | LHS | Sign | RHS |
| Transportability: | | 3 | -2 | 269995 | ≥ | 0 |
| Offroad Capability: | | 1 | -1 | 89998 | ≥ | 0 |
| Minimum MATV: | | | 1 | 1 | ≥ | 1 |
| Min JLTV | | 1 | | 89999 | ≥ | 1 |
| Min Total Vehicles: | | 1 | 1 | 90000 | ≥ | 90000 |
| | | | | | | |
| Solution | | 89999 | 1 | | | |
| | | | | | | |
| | | | | 80% Learning Curve= | | -0.321928095 |
| | | | | Theoretical cost of 1st JLTV= | | $ 10,000,000.00 |
| | | | | Theoretical cost of 1st M-ATV= | | $ 8,000,000.00 |

Figure 1. Results of the Model.

Given the assumptions and constraints, the optimum solution (Figure 1) is to produce 89,999 JLTVs and only 1 M-ATV. The unit cost for the JLTVs is $254,151 compared to $8,000,000 for 1 M-ATV, yielding a total cost of about $22.88 billion.

## C. SENSITIVITY ANALYSIS

Despite having identical learning curves and a theoretical first unit cost 25% higher than that of the M-ATV, producing JLTVs exclusively is less expensive than producing any combination of both vehicles. This is the result of the average grade requirement. Producing M-ATVs exclusively would be less expensive than producing JLTVs, but the result would be an average grade of 5 out of 10 for both transportability and off-road capability. Requiring an average grade of 7 for transportability and 6 for off-road capability necessitates producing enough JLTVs that the average grade of the fleet will be raised to the desired average grade. To reach the desired average grade for these two vehicles, a minimum of 45,000 JLTVs would need to be produced.

Producing 45,000 M-ATVs rather than 90,000 increases the cumulative average cost of each M-ATV from $203,000 to $254,000. Producing 45,000 of each vehicle satisfies the desired mixed grades, but costs $25.7 billion. However, producing 90,000 JLTVs and zero M-ATVs satisfies and even exceeds the desired mixed grades. Producing 90,000 JLTVs rather than 45,000 decreases the cumulative average cost from $317,000 to $254,000 and decreases the total cost to $22.9 billion. The added benefit is the average performance grades become 10 and 7 for transportability and off-road capability, respectively, which is better than the requirement for either.

One of two things has to happen in order for the model to favor purchasing M-ATVs over JLTVs. First, the theoretical first unit cost of the M-ATV must drop much lower than that of the JLTV. For example, if M-ATVs theoretical first unit cost was half that of JLTV, then it would be less expensive to produce the M-ATV and JLTV at a1:1 ratio while meeting the average performance goals. Second, if the average performance grades where much closer to the grades of the M-ATV than the JLTV, then less JLTVs would be needed to achieve the needed mix.

The model is sensitive to the desired average grades. Amongst the average grade constraints, transportability is the binding constraint. In order to identify an average transportability grade that would yield an optimum solution that suggests producing more M-ATVs than JLTVs, this thesis set the non-binding constraint, off-road capability, to a desired mixed grade equal to the grade of the M-ATV. This ensures off-road capability does not become the binding constraint while testing the sensitivity of the transportability constraint. For this thesis, the model is solved several times to accomplish “what if” type sensitivity analysis through adjusting the desired mixed grade in a bracketing fashion until the point at which the model begins to favor M-ATVs is identified. Figure 2 is a chart of the results.

| Mixed Grade | Optimal JLTVs | Optimal M-ATVs | TotalCost |
|---|---|---|---|
| 5.1875 | 90,000 | 0 | $ 22,873,501,753 |
| 5.125 | 2,250 | 87,750 | $ 19,862,425,856 |
| 5.0625 | 1,125 | 88,875 | $ 19,315,316,473 |
| 5 | 0 | 90,000 | $ 18,298,801,403 |

Figure 2. Mixed Grade Sensitivity.

Figure 2 shows that a desired transportability mixed grade of 5.1875 or greater results in an optimum ratio of 90,000 JLTVs and zero M-ATVs at a cost of $22.9 billion. A mixed grade of 5.125 begins to make purchasing M-ATVs optimum at a ratio of 87,750 M-ATVs and 2,250 JLTVs, and a total cost of $19.9 billion. A mixed grade of 5.0625 finds an optimum ratio of 88,875 M-ATVs to 1,125 JLTVs and a total cost of $19.3 billion. A mixed grade of 5 or less produces an optimum ratio that favors procuring 90,000 M-ATVs at a cost $18.3 billion.

The model is also sensitive to learning curve percentages. This thesis assumes an 80% learning curve for both vehicles. Sensitivity analysis shows the optimum ratio of JLTVs and M-ATVs is consistent for learning curves of 90% or less. Learning curves of 91% and higher find optimum ratios of nearly 1 JLTV for every 1 M-ATV. The conclusion here is that even when both vehicles have the same learning curve, the steepness of the curve affects the optimum ratio. At a 90% learning curve or steeper, procuring only JLTVs is the optimum solution. At a 91% learning curve or flatter (with 100% being flat) the optimum solution is to procure a mix of vehicles at nearly a 1:1 ratio.

What if the two vehicles do not have the same learning curve? Sensitivity analysis conducted near the 80% learning curve rate demonstrate that when the JLTV has an 81% learning curve compared to 80% for M-ATV, the optimum ratio does not change. However, when JLTV has an 82% learning curve compared to 80% for M-ATV, then the optimum ratio becomes 1 JLTV for every 1 M-ATV. The conclusion here is that relatively minor differences between the learning curve percentages for each vehicle can change the optimum ratio of vehicles to procure. Users of this decision tool should be as accurate as possible when selecting the learning curve for each vehicle, and should conduct a sensitivity analysis to determine how variations in their assumptions will affect the results.

The model is sensitive to the first unit cost of each vehicle. This thesis assumes a first unit cost of $10 million for the JLTV and $8 million for the M-ATV. If the JLTV's first unit cost was significantly higher than that of the M-ATV, then with all of the previous assumptions held constant, it is still possible that a mix of both vehicles becomes optimal compared to procuring only JLTVs. Seeking to find at which point the first unit cost would change the optimum solution, this thesis tested JLTV first unit costs compared to an $8 million first unit cost for the M-ATV. The optimum solution does not change until the first JLTV cost is $14 million or more. This demonstrates that at an 80% learning curve, the JLTV first unit cost can be significantly more than that of the M-ATV before the optimum ratio is changed.

Based on the assumed desired mixed grades, learning curve percentages, and the theoretical first unit costs of both vehicles, this model demonstrates that it is less expensive to produce only the JLTV than it is to produce any combination of both vehicles. Altering the desired mixed grade, learning curve percentages, or the theoretical first unit costs may change the results, so it is necessary for the user of the model to be as accurate as possible when assigning these factors in the model.

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# VI. CONCLUSION

## A. OVERVIEW

This study proposes using a non-linear programming optimization model as a decision making tool to identify the optimum ratio of JLTVs and M_ATVS to be jointly procured by the U.S. Army and the Marine Corps.

The U.S. Army and the Marine Corps have already procured more than 8,000 M-ATVs and are in the process of procuring up to 90,000 thousand JLTVs by year 2015. The two vehicles share many of the same characteristics and are designed to perform nearly identical missions. The redundancy between the two vehicles has drawn some criticism and concern over wasteful spending.

The model developed in this thesis provides an analytical framework to view and analyze the decision problem faced by the Army and the Marine Corps. Specifically, the model built in this thesis seeks to minimize procurement costs while considering redundancy issues and required capabilities by the supported missions. This tool is not limited in its usefulness to this single decision problem. It can be applied to any number of other platforms or expanded to consider more than two options. For example, this decision making tool can be used to identify an optimum mix of manned or unmanned aircraft, or to find the optimum ratio of various platforms for the littoral combat ships. Any scenario that seeks an optimum, cost minimizing ratio of manufactured products can benefit from the use of this tool.

## B. SUMMARY OF MAIN FINDINGS

The solution identified by the model is heavily influenced by assumptions, therefore the model is presented as a decision making tool and not as a call to action. As data becomes available, this model can be utilized over and over again to incorporate the updated data and to find the optimum solution.

When solved using the assumptions described in Chapters III and IV, the model finds that the optimum ratio of JLTVs and M-ATVs that the Army and Marine Corps should purchase is 90,000 JLTVs and zero M-ATVs at a total cost of $22.9 billion. This result suggests the Army and Marine Corps should not procure any more M-ATVs, rather the two services should purchase only JLTVs for the for their light tactical wheeled vehicle fleets.

The decision model in this thesis shows that although the JLTV is initially more expensive to procure (~$10,000,000/unit compared to ~$8,000,000/unit), the rapid initial reduction in costs realized via efficiencies demonstrated in learning curve savings make procurement of only one or the other vehicle the only viable option. A mix of both vehicles only becomes cost effective in a very narrow range when both vehicles have nearly identical performance grades on the binding constraint (in this model the binding constraint is transportability). Because procuring a mix of both vehicles only becomes the least expensive course of action under extremely narrow conditions, the user of this model is unlikely to encounter a scenario where procuring both vehicles is the least expensive procurement method.

## C. RECOMMENDATION

Based on the assumptions and results of the optimization model used in this thesis, the formulated recommendation is for the Army and Marine Corps to not procure any more M-ATVs and procure only JLTVs to meet the mission requirements these vehicles were designed to meet. In procuring only JLTVs, the services build a more capable fleet of vehicles than any mix of both vehicles would produce. Additionally, procuring only JLTVs is less expensive than procuring any mix of both vehicles.

Procuring only M-ATVs is less expensive than procuring only JLTVs, but the services would lack critical capabilities in their fleet that both services require. Chief among these is the ability to transport the vehicle via helicopter. The M-ATV remains too heavy to be transported via either the Army’s CH-47 or the Marine Corps’ CH-53 helicopters. In order to add this capability to the fleet of vehicles, at least a portion of the vehicles will have to be JLTVs. Once JLTVs become a requirement for at least a portion of the fleet, it becomes less expensive to build the entire fleet of only JLTVs.

## D. POTENTIAL FOR FURTHER RESEARCH

Procurement costs are only a fraction of the total cost involved in a program. One potential area for future research is to develop a model that can incorporate life cycle cost estimates into a non-linear programming model. Life cycle costs could be of even greater value to a decision maker than procurement costs, but may contain too many variables to be useful in a model similar to this one. Future research in this area would be useful.

Assigning grades to vehicle characteristics is a subjective process which opens the door to undue bias in the model. Development of a tool that can objectively assign quantifiable grades to vehicle characteristics would reduce bias and increases the usefulness of this model. Future research in this area would be useful.

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# LIST OF REFERENCES


Beidel, E. (2012, April). Officials look for ways to upgrade humvees after recap cancellation. *National Defense Magazine*, Retrieved from http://www.nationaldefensemagazine.org/archive/2012/April/Pages/OfficialsLookforWaystoUpgradeHumveesAfterRecapCancellation.aspx

Defense Industry Daily. (2012, May 30). M-atv: A win, at last, for Oshkosh. *Defense Industry Daily*. Retrieved from http://www.defenseindustrydaily.com/M-ATV-A-Win-at-Last-for-Oshkosh-05602/

Erwin, S. I. (2011, February). Uncertain path ahead for military truck fleet. *National Defense Magazine*, Retrieved from http://www.nationaldefensemagazine.org/archive/2012/April/Pages/OfficialsLookforWaystoUpgradeHumveesAfterRecapCancellation.aspx

Feickert, A. Library of Congress, Congressional Research Service. (2012). *Joint Light Tactical Vehicle (JLTV): Background and issues for Congress*. Retrieved from http://www.fas.org/sgp/crs/weapons/RS22942.pdf

Goodman, G. (2011, November 22*). Joint Light Tactical Vehicle: Usmc peo land systems programs 2011–2012.* Retrieved from http://www.defensemedianetwork.com/stories/joint-light-tactical-vehicle-2/

John-Givens, A. (2012, January 29). Army drives ahead with Joint Light Tactical Vehicle program. *Armed Services and Government News*. Retrieved from http://infoweb.newsbank.com.libproxy.nps.edu/iw-search/we/InfoWeb

Render, B., Stair Jr., R, & Balakrishnan, N. (2003). *Managerial decision modeling with spreadsheets.* Upper Saddle River, NJ: Pearson Education, Inc.

U.S. Department of the Army. U.S. Department of the Army, Office of the Vice Chief of Staff. (2010). The army tactical wheeled vehicle strategy. Retrieved fromhttps://www.g8.army.mil/pdf/The_Army_TWV_Strategy.pdf

U.S. Government Accountability Office. (2010, November). Issues to be considered as DoD modernize its fleet of tactical wheeled vehicles. (Publication No. GAO-11–83). Retrieved from http://www.gao.gov/new.items/d1183.pdf

U.S. Government Accountability Office. (2011, March). *Opportunities to reduce potential duplication in government programs, save tax dollars, and enhance revenue* (Publication No. GAO-11–318SP). Retrieved from http://www.gao.gov/new.items/d11318sp.pdf

U.S. Government Accountability Office Testimony. (2011, October 26). Testimony Before the Subcommittee on Tactical Air and Land Forces, Committee on Armed Services, House of Representatives. *Future Ground-Based Vehicles and Network Initiatives Face Development and Funding Challenges.* (Publication No. GAO-12–181T). Retrieved from http://www.gao.gov/assets/590/585939.pdf

U.S. Government Accountability Office. (2012, February). Follow-up on 2011 report: Status of actions taken to reduce duplication, overlap, and fragmentation, save tax dollars, and enhance revenue. (Publication No. GAO-12–453SP). Retrieved from http://www.gao.gov/assets/590/588891.pdf

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